

Measuring the Upper End of the Initial Mass Function with Supernovae

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Abstract. Supernovae arise from progenitor stars occupying the upper end of the initial mass function. Their extreme brightness allows individual massive stars to be detected at cosmic distances, lending supernovae great potential as tracers of the upper end of the IMF and its evolution. Exploiting this potential requires progress in many areas of supernova science. These include understanding the progenitor masses that produce various types of supernovae and accurately characterizing the supernova outburst and the environment in which it was produced. I present some preliminary work identifying the environmental conditions that produce the most luminous supernovae, believed to arise from stars with masses greater than $100 M_{\odot}$. I illustrate that the presence of these extreme supernovae in small star-forming dwarfs can be used to test our understanding of the upper end of the IMF.

1. Motivation

Supernovae (SNe) are the spectacular end result of massive star evolution. Current estimates of the lower mass limit for SN progenitors are near $8 M_{\odot}$ (e.g., Smartt et al. 2009), making them extremely relevant to studies of the upper end of the initial mass function (IMF). The fact that SNe are now being detected beyond $z = 2$ (Cooke et al. 2009) adds the potential to use SNe as tracers of IMF evolution. Their usefulness depends on how well their progenitors can be understood and how well the observations of SNe can constrain the distribution of progenitor masses. In addition, we must be able to characterize the host galaxies of SNe and connect them to our general understanding of star formation in galaxies at various stages of their evolution.

2. SN Wish List

Let us take an idealized view of SNe and list what they have to offer for studies of the upper-IMF. For a given galaxy with a given star formation history (SFH) or current star formation rate (SFR), we would like to know: what is the mass of the largest star that can be produced? This is a fiducial point in the IMF that calibrates the relationship between the IMF and the host SFR (e.g., Weidner et al. 2010). The fact that such massive stars are bright is offset by their very short lives, making them difficult to observe. The SN explosion marks these massive stars in events detectable across cosmic distances. Provided we can decode the progenitor mass and measure the host galaxy SFH/SFR,

we can directly calibrate this important fiducial point in a system's IMF, and trace its evolution potentially out beyond $z = 2$.

If we know the masses of not just the most massive SN progenitors, but a whole range of progenitors down to the $8 M_{\odot}$ limit, we can measure the distribution of massive stars from 8 to over $100 M_{\odot}$ as a function of host SFR/SFH and mass and, while we are at it, metallicity. Assuming we have stellar evolution models for these massive stars that will provide us with their lifetimes, we can then look into the evolution of clusters with greater accuracy, revealing how energy and processed metals are re-introduced into the birth cloud of our idealized SN progenitors.

Now that we have imagined this ideal universe in which understanding the upper end of the IMF rests only on the collection of enough SNe and the corollary host data to sample the distributions well enough, let us now look at the reality of SN progenitors and how close we can get to this idealized situation.

3. Reality

Type	Mechanism	Character	Mass (M_{\odot})	Progenitor
Ia	Thermonuclear	mass-transferring binary	3 – 8	CO WD
II(P,L,n)	Core-Collapse	H in absorption (emission)	7 – 25	R/BSG
IIb	Core-Collapse	weak H similar to He	15 – 25	(late) WN
Ib	Core-Collapse	all H removed	25 – 40	(early) WN
Ic	Core-Collapse	all H, He removed	40 – 80	WC/WO
II _n -lum	Core-Collapse	narrow H emission	80 – 150	LBV
I _{pec}	pulsational pair?	all H, He removed	80 – 150	W-R?
I-PP	pulsational pair	Fe-group but no H, He	>100	pop III?

Table 1. SN Types

I will briefly outline the menagerie of SN types and what we know about their progenitors. I have summarized the basic properties of SNe of various types in Table 1 after the scheme presented in Gal-Yam et al. (2007). SNe are divided roughly into two categories depending on the presence (type II) or absence (type I) of hydrogen, either in emission or absorption, in their spectra. When we attribute physical processes to the SN explosions it becomes clear that a more rational division is between those explosions caused by the collapse of a massive stellar core (core-collapse, or CC SNe) and those explosions caused by the thermonuclear burning of a carbon-oxygen white dwarf (thermonuclear, or type Ia SNe). We will not consider the thermonuclear SNe, since we know they arise in binary systems (for a review, see Livio 2001) and it is unlikely that their progenitors arise from stars more massive than $8 M_{\odot}$, otherwise they would produce CC SNe.

Within the CC SN types, there appears to be a natural progression of atmospheric depletion due to mass loss of varying efficiency. The least depleted are the type II SNe that show hydrogen lines. These SNe are further sub-divided by light curve shape (II-P for ‘plateau’ and II-L for ‘linear decline’) and the presence of narrow emission lines (II-n), indicating the interaction of the SN ejecta with surrounding circum-stellar material.

The type IIb SNe represent the next level of depletion in which helium lines are as strong or stronger than the hydrogen lines. Type Ib SNe occur when the atmospheric depletion is so complete that only helium lines are seen. The most depleted objects are the type Ic SNe, showing neither hydrogen nor helium lines in their spectra. Some of these depleted objects have cores so massive that they undergo a pulsational pair-production instability which eventually produces a very luminous explosion. These are the pair instability SNe (PISNe) that have been theoretically predicted for decades (Barkat et al. 1967; Bond et al. 1984; Heger & Woosley 2002; Waldman 2008), but only recently confirmed observationally (Gal-Yam et al. 2009; Quimby et al. 2009).

The cause of the mass loss that depletes the hydrogen and helium is some combination of low surface gravity, stellar winds, and binary interaction. This leads to significant uncertainty when estimating progenitor initial masses. We know that metallicity plays a role in determining the efficiency of wind-driven stellar mass loss, but there is significant uncertainty in this theory. The ugly reality is that the type of the SN derives from some unknown combination of metallicity, binary interaction, and initial stellar mass, clouding our vision of SNe as ideal probes of the upper IMF.

As of today, the best constrained SN progenitors are the least depleted ones near the lower mass limit. Smartt et al. (2009) report pre-explosion multi-band photometry of at least seven SNe II-P and limits on another 13. These result in initial mass estimates for the progenitors in the range from $\sim 7 - 25 M_{\odot}$. This is a good beginning, but this sample represents a small fraction of the population of SN II SNe. There is no way to calculate an initial mass distribution from this small sample.

4. The Dawning Time-Domain Era

Survey	Tel.	FOV	Filters	Cadence	Depth/day	Coverage
PTF	1.2m	7°	gR	1-5day	~ 21 mag	$8000^{2\sigma}/\text{yr}$
PanSTARRS	1.8m	7°	grizy	4day	22.3(y), 25.1(i)	$3\pi - 30,000^{2\sigma}$
CSS	0.7m	8°	unflt.	1day	~ 20 mag	$1200^{2\sigma}/\text{dy}$
SkyMapper	1.3m	6°	uvgriz	4hrs-1yr	~ 22 (g)	$2\pi - 26,000^{2\sigma}$
LSST	6.5m	10°	ugrizy3	3day	24.5(r)	$3300^{2\sigma}/\text{dy}$

Table 2. Current and Future Transient Surveys

There is no doubt that progress on the upper IMF requires improvements in the theory of high-mass stellar evolution. More precise and diverse models of SN explosions will also help in deciphering progenitor characteristics from the spectra of SNe in outburst. The engine capable of driving meaningful theoretical progress is a more comprehensive and representative data set covering the full diversity of SN explosions. We are on the verge of a quantum jump in the quality and the quantity of observations of SNe in outburst with wide-field transient surveys like PanSTARRS (Hodapp et al. 2004), PTF (Law et al. 2009), CSS (Drake et al. 2009), SkyMapper (Keller et al. 2007) already online and others such as LSST (Ivezic et al. 2008) coming online in the future.

These surveys, summarized in Table 2, take advantage of wide-field detectors on robotically controlled telescopes to produce large area time-domain surveys that are

already having an impact on our understanding of SN demographics. Old SN surveys used narrow-field detectors and were necessarily host-targeted, producing biases tied to the luminosity and mass of hosting galaxies. The new areal searches are not only removing these biases, but are discovering new types of SNe.

These surveys have the potential to vastly improve our measurements of SN demographics and produce accurate distributions of types and rates of each type. With the proper followup, these rates can be correlated with host galaxy SFR, stellar mass, and average metallicity. They have already shown their value by discovering a new type of extremely luminous SN, but it is likely that other rarities will be discovered as well.

5. Tantalizing Highlight: Extreme SNe in Extreme Hosts

The first addition to the SN menagerie made by these areal SN surveys already shows the power of comprehensive surveys to illuminate regions of parameter space that have been in darkness up to now. Because of the host targeted bias, necessitated by narrow field searches, the SNe in faint hosts have been passed over. It turns out that the most luminous SNe on record are typically found in faint, small dwarf galaxies (Young et al. 2010; Gal-Yam et al. 2009; Quimby et al. 2009). These luminous SNe (LSNe) include very luminous explosions showing narrow emission lines that help to power the later light curve and are known as SNe IIn-lum. There is another set of LSNe that show no H in their spectra, but have unusual light curves and spectra when compared to any other SN type. These we call SNe Ipec.

Recent analysis shows that two LSNe (SN1999as and SN2007bi) show strong evidence of having been produced as the result of the pulsational pair instability process (Gal-Yam et al. 2009), hence we label them Ic-PP. Their light curves are consistent with models of extreme LSNe that produce $> 10^{52}$ ergs of total energy implying the radioactive decay of a large amount ($> 4M_{\odot}$) of ^{56}Ni . Their spectra show the results of this ^{56}Ni decay by having a high abundance of Fe-group elements (Gal-Yam et al. 2009). These signatures require a very massive initial mass for the progenitor star, upwards of $150 M_{\odot}$. There is also evidence that the progenitor of SN2007bi was a single star (Gal-Yam et al. 2009). It is possible that some of the SNe Ipec that have similar properties may also be PISNe, but they may not be as extreme.

We analyzed the hosts of seventeen LSNe (Neill et al. 2010) using *GALEX* (Martin et al. 2005) and SDSS (York et al. 2000) images to derive their UV-optical colors and estimate their stellar masses (M_*) and specific SFR ($s\text{SFR} = \text{SFR}/M_*$). We compare them to a larger sample of nearby galaxies (Wyder et al. 2007) to illustrate how extreme the hosts are and to determine what phase of galaxy evolution might be demarcated by LSNe in such small galaxies. While the incompleteness in the comparison sample at the faint end prevents a determination of the relative space density of LSNe producers, one can see (Figure 1) that LSNe appear to prefer small star-bursting dwarfs.

The LSN hosts have low total SFR, but high sSFR due to their low masses. The progenitor of one of the LSNe (SN2007bi) may exceed $150 M_{\odot}$. Any theory of the IMF that posits an upper limit to the most massive star produced based on current SF must account for these cases, which may be considered limiting. To illustrate this, consider Figure 4 of Pflamm-Altenburg et al. (2007). Here we see that for SFRs near $10^{-1} M_{\odot} \text{ yr}^{-1}$, a $150 M_{\odot}$ star is just barely consistent. This is probably good news for

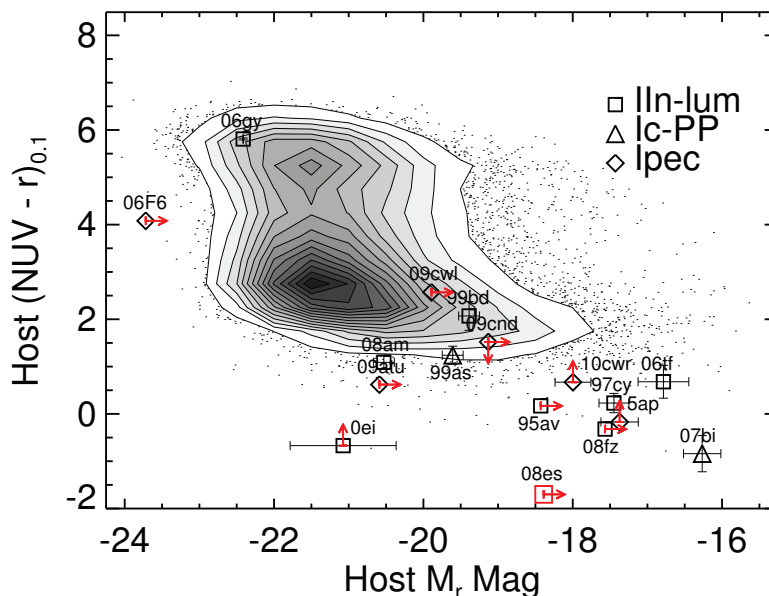


Figure 1. Galaxy $NUV - r$ versus M_r CMD with extreme SNe indicated (Neill et al. 2010). SN types are indicated by the symbols with IIn-lum SNe indicated by squares, Ic-PP SNe (PISNe) indicated by triangles, and Ipec SNe indicated by diamonds. Right pointing arrows indicate which half-plane the particular LSN host is limited to by the UV-optical photometry, upward pointing arrows indicate that the $NUV - r$ color must be redder than the symbol, while the double arrows for PTF09cnd indicate the quarter-plane that its host is limited to. The contours represent the galaxy density per bin (0.5 by 0.5 mag) of the comparison sample which is derived from the *GALEX* – SDSS cross-match presented in Wyder et al. (2007). The darkest contour indicates a density of 1056 galaxies per bin, while the lightest bin is at 132 galaxies per bin. Below the minimum contour galaxies are plotted individually as small points. The LSN hosts appear to favor hosts on the blue side of the blue cloud, toward the low-luminosity end.

such theories, because these object are indeed rare. Currently the errors on both the host SFR and the progenitor initial mass are large, but as these shrink, the LSNs and their hosts could drive a re-calibration of IMF theories that predict the mass of the most massive star produced based on current star formation.

6. Conclusions

While the reality of using SNe to map out the entire upper end of the IMF appears to be a long way off, there is cause for hope for the future. Large area surveys will produce unbiased samples of SNe, allowing us to test and improve theories of SN progenitors

and their production. Even though we may never be able to map out the distribution of high mass stars with SNe, it does seem likely that LSNe may arise from some of the most massive stars known, providing a crucial calibration point in IMF theory. The fact that LSNe appear to favor small galaxies with low mass, low intrinsic SFR, but high sSFR makes them even more useful to advancing IMF theory.

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